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PRELIMINARY EVALUATION OF BIODIESEL BLENDS BY USING A SINGLE-CYLINDER MEDIUM-SPEED DIESEL ENGINE

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BY

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ENGINE SYSTEMS DEVELOPMENT CENTRE

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Since some of the accepted measures in the industry are imperial, metric measures are not always used in this report.

Un sommaire français se trouve avant la table des matières.

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16. Abstract

Six biodiesel blends (low sulphur #2Diesel and frying oil-based biodiesel or canola-based biodiesel at three different concentrations – 5%, 20% and 100%) were tested in a single-cylinder four-stroke medium-speed diesel engine under three operating modes. Engine performance and emissions data obtained with the blends were compared with those of an engine running with #2Diesel.

The 5% biodiesel blends could maintain engine power and fuel economy. The 5% and 20% frying oil-based biodiesel blends (FB5, FB20) and the 20% canola-based biosesel blend (CB20) reduced engine carbon monoxide (CO), particulate matter (PM) and smoke emissions, but increased oxides of nitrogen (NOx) emissions. It was also found that the 5% canola-based biodiesel blend (CB5) reduced CO, NOx,, smoke emissions and brake-specific fuel consumption (BSFC), but had no significant effects on PM and total hydrocarbon (THC) emissions. When engine fuel rates were maintained constant, the baseline PM and THC emissions were increased with the 100% biodiesel blends. Engine high-speed data, such as cylinder pressure and injection pressure, was also collected to provide support information for the evaluation of fuel economy and emissions benefits of using the blends.

Based on the test results and in consideration of other factors such as fuel cost issues, the CB5, FB5 and FB20 are recommended for further investigation in actual locomotives/locomotive engines.

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16. Résumé

Six mélanges de biodiésel (mazout numéro 2 à faible teneur en soufre et biodiésel à base d'huile à friture ou biodiésel à base de canola, à trois concentrations différentes – 5 %, 20 % et 100 %) ont été soumis à des essais dans un moteur monocylindre à quatre temps à régime moyen, selon trois modes de fonctionnement. Les données sur le rendement du moteur et les émissions produites dans chaque cas de figure ont été comparées à celles d'un moteur brûlant du mazout numéro 2.

Les mélanges à 5 % de biodiésel ont permis de maintenir constantes la puissance du moteur et la consommation de combustible. Les mélanges à 5 % et à 20 % de biodiésel à base d'huile à friture (FB5 et FB20), de même que le mélange à 20 % de biodiésel à base d'huile de canola (CB20), ont mené à une réduction des émissions de monoxyde de carbone (CO), de particules (PM) et de fumée, mais à une augmentation des émissions d'oxydes d'azote (NO_X). En outre, le mélange à 5 % de biodiésel à base d'huile de canola (CB5) a entraîné une réduction des émissions de CO, de NO_X et de fumée, de même que de la consommation spécifique de carburant, mais n'a pas eu d'effet significatif sur les émissions de particules et d'hydrocarbures totaux (HCT). À débits d'injection constants, les émissions de particules et de HCT augmentaient avec l'utilisation des «mélanges» à 100 % de biodiésel. Des données sur le moteur fonctionnant à plein régime (pression dans le cylindre et pression d'injection) ont également été colligées afin d'appuyer l'évaluation des avantages offerts par les mélanges de biodiésel aux chapitres de la consommation et de la réduction des émissions.

D'après les résultats des essais et à la lumière d'autres facteurs (notamment le coût du combustible), il est recommandé de poursuivre les recherches sur les mélanges CB5, FB5 et FB20 dans des locomotives/moteurs de locomotives en vraie grandeur.

17. Mots clés	18. Diffusion
Rendement du moteur, émissions, mélange de biodiésel, combustible diesel, carburant de remplacement, moteur diesel à régime moyen, moteur de locomotive	Le Centre de développement des transports dispose d'un nombre limité d'exemplaires.

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EXECUTIVE SUMMARY

Six biodiesel blends were prepared at ESDC's lab. These were mixtures of low sulphur #2Diesel and biodiesel of two origins (frying oil and canola) at three different concentrations (5%, 20% and 100%). The frying oil and canola biodiesel were from Canadian resources. A soybean biodiesel from the U.S. was also selected for this program; however, due to delivery problems, it could not be obtained within the project time frame.

The biodiesel blends and the #2Diesel were tested in a single-cylinder medium-speed diesel research engine. The tests were conducted under three steady-state engine modes representing engine full load, about 50% power, and idle condition. During a fuel test, data on engine operating parameters, exhaust emissions, cylinder combustion pressure and fuel injection pressure was collected. The injection needle lift data could not be obtained due to transducer failure.

The Association of American Railroads (AAR) three-mode duty cycle factors were applied to calculate weighted emissions and brake-specific fuel consumptions (BSFCs). Results are summarized in Table 1.

Table 1: Emissions and BSFC Data Summary

	CO (g/kW-h)	NOx (g/kW-h)	THC (g/kW-h)	PM (g/kW-h)	BSFC (lb/hp-h)
#2Diesel	3.1	16.7	0.20	0.16	0.401
FB5 (5% frying oil-based biodiesel blend)	3.0	18.1	0.20	0.14	0.402
FB20 (20% frying oil-based biodiesel blend)	2.5	18.0	0.20	0.13	0.404
FB100 (100% frying oil-based biodiesel blend)	2.2	28.3	0.24	0.25	0.425
CB5 (5% canola-based biodiesel blend)	2.9	16.5	0.19	0.16	0.399
CB20 (20% canola-based biodiesel blend)	2.7	17.9	0.20	0.14	0.402
CB100 (100% canola-based biodiesel blend)	2.2	25.4	0.23	0.26	0.411

Engine high-speed data (heat release rate and fuel injection pressure) provided additional information for understanding the effects of biodiesel blends on engine performance and emissions. It was found that the combustion ignition delay and peak heat release rate at the premixing period were reduced with increasing percent biodiesel. For the same fuel rate, 5% and 20% biodiesel blends had similar fuel injection patterns as that of the #2Diesel.

SOMMAIRE

Six mélanges de biodiésel ont été préparés au laboratoire de ESDC, soit des mélanges composés de mazout numéro 2 à faible teneur en soufre et de deux biodiésels (l'un à base d'huile à friture et l'autre de canola), à trois concentrations différentes (5 %, 20 % et 100 %). Les biodiésels à base d'huile à friture et de canola provenaient de fournisseurs canadiens. Un biodiésel à base de soya en provenance des États-Unis avait également été choisi pour le programme; cependant, en raison de problèmes de livraison, il n'a pu être obtenu dans les délais du projet.

Des essais sur les mélanges de biodiésel et sur le mazout numéro 2 ont été réalisés dans un moteur d'essai monocylindre à régime moyen. Le moteur fonctionnait à trois régimes permanents, soit à plein régime, à environ 50 % de sa puissance et au ralenti. À chaque essai, des données sur les paramètres de fonctionnement du moteur, les émissions, la pression dans le cylindre et la pression d'injection étaient recueillies. Les données sur la levée de l'aiguille de l'injecteur n'ont pu être obtenues en raison d'une défaillance du transducteur.

Les facteurs de l'Association of American Railroads (AAR) applicables aux trois cycles d'utilisation étudiés ont servi à calculer les données pondérées d'émissions et de consommation spécifique de carburant. Les résultats sont résumés dans le tableau 1.

Tableau 1 : Résumé des données sur les émissions et la consommation spécifique de carburant

	CO (g/kW.h)	NO_x (g/kW.h)	HCT (g/kW.h)	PM (g/kW.h)	BSFC (lb/hp.h)
Mazout numéro 2	3,1	16,7	0,20	0,16	0,401
FB5 (mélange à 5 % de biodiésel à base d'huile à friture)	3,0	18,1	0,20	0,14	0,402
FB20 (mélange à 20 % de biodiésel à base d'huile à friture)	2,5	18,0	0,20	0,13	0,404
FB100 («mélange» à 100 % de biodiésel à base d'huile à friture)	2,2	28,3	0,24	0,25	0,425
CB5 (mélange à 5 % de biodiésel à base d'huile de canola)	2,9	16,5	0,19	0,16	0,399
CB20 (mélange à 20 % de biodiésel à base d'huile de canola)	2,7	17,9	0,20	0,14	0,402
CB100 («mélange» à 100 % de biodiésel à base d'huile de canola)	2,2	25,4	0,23	0,26	0,411

Les données sur le moteur à plein régime (vitesse de combustion et pression d'injection) permettent de mieux comprendre les effets des mélanges de biodiésel sur le rendement du moteur et sur les émissions. Ainsi, on a constaté que le délai d'allumage et la vitesse de

combustion maximale à l'étape de prémélange diminuaient lorsque le pourcentage de biodiésel dans le mélange augmentait. Pour un même débit d'injection, les mélanges à 5 % et à 20 % présentaient des formes de jets d'injection semblables à ceux du mazout numéro 2.

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GLOSSARY

AAR	Association of American Railroads
AVL	AVL LIST GMBH (Austria)
BSFC	Brake Specific Fuel Consumption
BSE	Brake Specific Emissions
B5	Biodiesel blend containing 5% (volume) biodiesel and 95% (volume) diesel
B20	Biodiesel blend containing 20% (volume) biodiesel and 80% (volume) diesel
B100	Biodiesel blend containing 100% (volume) biodiesel and 0% (volume) diesel
CB5	Canola-based B5
CB20	Canola-based B20
CB100	Canola-based B100
CFR	Code of Federal Register (U.S.)
CO_2	Carbon dioxide
CO	Carbon monoxide
C_xH_y	Combustible
ECOM	ECOM America, Ltd.
EMD	Electro-Motive Division of General Motors Corp.
EPA	Environmental Protection Agency (U.S.)
ESDC	Engine Systems Development Centre, Inc.
FB5	Frying oil-based B5
FB20	Frying oil-based B20
FB100	Frying oil-based B100
FIP	Fuel Injection Pressure
FS	Full Scale
GE	General Electric Company
HRR	Heat Release Rate
NO	Nitric oxide
NO_2	Nitrogen dioxide
NOx	Oxides of nitrogen
O_2	Oxygen
PCB	Polychlorinated Biphenyl
PM	Particulate Matter
SCRE	Single-Cylinder Research Engine
THC	Total Hydrocarbon
TM	Test Mode

1.0 INTRODUCTION

Tests were conducted at Engine Systems Development Centre, Inc. (ESDC) to evaluate the effects of biodiesel blends on the performance and emissions of a single-cylinder medium-speed diesel engine. The main objective of this work was to gain initial information and experience about biodiesel for railway application based on which candidate biodiesel blends œuld be recommended for further investigation on actual locomotives.

Two types of biodiesel fuels (frying oil and canola) from Canadian resources were tested in this program. The frying oil biodiesel is produced from wasted restaurant oil (main fraction is vegetable oil) at low cost. It was supplied by Rothsay of Ste-Catherine, Quebec. The high quality and expensive canola biodiesel was supplied by Milligan Biotech Inc. of Foam Lake, Saskatchewan. It was claimed by the two biodiesel processing companies that the supplying capacity of biodiesel fuels can be 85 million litres per year in next five years. This will make biodiesel application feasible for Canadian railways. Soybean biodiesel supplied by a U.S. resource was also planned to be tested in this program since it was popular with many engine applications. However, due to delivery problems, it was not available during the time frame of this project.

This report provides an overview of the technical program used to conduct the evaluation tests and the test results.

2.0 TEST DESCRIPTION

2.1 Test Engine

The test engine used was a single-cylinder four-stroke medium-speed diesel research engine with 9.0 in. bore and a 10.5 in. stroke. The engine was a research version of AlCO-251. The engine specifications are shown in Table 1 and the picture of the engine is shown in Figure 1.

Table 1: SCRE-251 Specifications

Cylinder	1
Engine Stroke	4
Bore x Stroke	9.0 in. (228.6 mm) x 10.5 in. (266.7 mm)
Displacement	668 cu. in. (10.9 L)
IMEP (max)	23 bar (334 psi)
Engine Speed (max)	1200 rpm
Idle Speed (Normal)	400 rpm
Compression Ratio	11.5:1 (Variable)
Fuel Injection Type	Direct Injection
Fuel Injector	9 holes × 0.40 mm × 145°
Fuel Injection Timing	27.5° CA BTDC (Variable)
Governing	Electronic

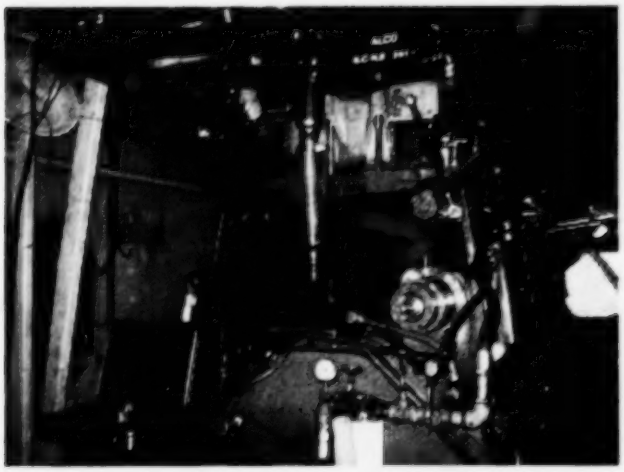

Figure 1: SCRE-251 in Test Cell

2.2 Test Fuel

The engine baseline test was performed using standard low sulphur #2Diesel. Specifications of the fuel are shown in Table 3.

A canola-based biodiesel and a frying oil-based biodiesel were mixed with the #2Diesel at three different volume percentages (5%, 20% and 100) to obtain six biodiesel blends, as shown in Table 2. Fuel properties of these fuel blends are given in Table 3.

Table 2: Biodiesel Blends

Biodiesel	Base Fuel	Volume Percentage of Biodiesel in a Blend	Index
Canola Biodiesel	#2Diesel	5	CB5
		20	CB20
		100	CB100
Frying Oil Biodiesel	#2Diesel	5	FB5
		20	FB20
		100	FB100

The biodiesel blends were prepared at ESDC's lab using a mixing pump. Three totes (Figure 2) were used to store three different biodiesel blends during a biodiesel test.

Table 3: Properties of Test Fuels

Fuel Property		ASTM	Fuels						
			#2Diesel	FB100	FB20	FB5	CB100	CB20	CB5
Density @ 15°C (kg/L)		D1298	0.8072	0.8815	0.8219	0.8118	0.8827	0.8223	0.8112
Flash point (°C)		D93	43.0	165.0	40.5	47.5	144	49.0	47.0
Cloud point (°C)		D2500/D5773	-49	6.0	-19	-35	-2.4	-24	-38
Pour point (°C)		D97	-54	\	\	\	\	\	\
Viscosity @ 40°C (cSt)		D445		5.1			4.396		
Distillation	- Initial boiling point (°C)	D86/D1160	160	317	\	\	344	\	\
	- 10% recovered (°C)		177	326	\	\	351	\	\
	- 50% recovered (°C)		206	337	\	\	353	\	\
	- 90% recovered (°C)		257	337	\	\	355	\	\
	- Final boiling point (°C)		297	337	\	\	358	\	\
	- Loss (%)		0.5	\	\	\	\	\	\
	- Residue (%)		0.5	\	\	\	\	\	\
Ash (%, mass)		D482	< 0.01	\	\	\	\	\	\
Sulfated ash (%, mass)		D874	\	0.011	\	\	0.002	\	\
Copper strip corrosion		D130	1B	1A	\	\	1A	\	\
Water & sediment (%, v/v)		D1796/2709	<0.025	0.010	\	\	0.000	\	\
Sulfur (ppm, mass)		D129/2622/5453	450	<150	\	\	2	\	\
Gross heating value (kJ/kg)		D240	46238	40027	44911	45920	39069	44871	45718
Carbon residue (%, mass)		D189/4530	0.013	0.03	\	\	0.001	\	\
Cetane index		D976	44.1	\	43.8	43.5	\	44.0	44.1
Cetane number		D813	\	58	\	\	62.7	\	\
Acid number (mg KOH/mg)		D664	\	0.42	\	\	0.22	\	\
Free glycerin (%, mass)		D6584	\	0.000	\	\	0.006	\	\
Total glycerin (%, mass)		D6584	\	0.156	\	\	0.092	\	\

Figure 2: One of the Three Totes Used for Biodiesel Blends Storage

2.3 Engine Power and Fuel Consumption Measurement

The speed of the engine was controlled by an electronic engine governor. Engine speed was measured by an electronic-magnetic speed pick-up with accuracy of ±0.1% FS. The load on the engine was controlled and measured by the Schenk D1100 hydraulic dynamometer, which has an accuracy of ±0.5% FS. The fuel consumption rate was determined using the gravimetric method. The net fuel consumption rate was measured using a single-channel microprocessor-based monitor (Visipak VIP524W, ±0.01% FS accuracy) connected to a load cell carrying the weighing tank. A data acquisition and engine control system was used to monitor engine operating conditions and to record experimental data during the tests. Average engine speed, load and fuel consumption data were obtained at each test mode for calculations.

2.4 Cylinder Pressure and Fuel Injection Pressure Measurement

A high-temperature AVL pressure transducer was mounted in the engine cylinder head to measure cylinder pressure. The linearity of the transducer is less than ±0.2% FS. The fuel injection pressure was measured by using a PCB transducer with linearity of 0.58% FS. The engine crank-angle position was determined using an optical encoder. The data collections were performed by a computerized data acquisition system.

2.5 Exhaust Emissions Measurement

An emission sample probe was mounted in the exhaust stack to sample engine exhaust after a complete mixing of the exhaust gases in the surge tank. The gas samples were drawn from the engine exhaust stack via a high-flow pump assembly with an in-line water trap and particulate filter for proper conditioning prior to the electrochemical gas sensors of the portable ECOM AC+ analyzer. The analyzer is capable of detecting concentrations of carbon monoxide (CO), oxygen (O_2), combustibles (C_xH_y), nitric oxide

(NO), and nitrogen dioxide (NO_2), while also calculating carbon dioxide (CO_2). The accuracy of each of these sensors is within 2% of reading. A smoke opacity meter was installed in-line of the exhaust stack to determine engine smoke values. The linearity of the smoke meter is 1% from 0~100 opacity. Particulate matters (PM) were determined using a particulate emissions measuring system, which was designed with EPA 40CFR Part 92 specifications [1].

2.6 Test Procedure

Triplicate runs were performed to test the #2Diesel and each of the biodiesel blends. The test sequence (Table 4) was arranged randomly to minimize the effects of environmental conditions on the evaluation results. Each run sequence consisted of operating at three engine modes – TM1, TM2 and TM3 – for a total of about two hours. The test modes represented idle, approximately 50% power, and engine full load, respectively. During the runs, engine intake air temperature, intake air pressure, engine speed, fuel consumption rate, temperature of coolant engine out and temperature of oil at sump were maintained as closely as possible for the same test mode. Engine brake horsepower, fuel consumption rate, cylinder pressure and exhaust emissions were recorded for comparison analysis. Details on the test modes and data to be collected are shown in Table 5.

Table 4: Test Sequence

Test Day #	Index	Fuels	Run #
Day-1	1	#2Diesel	1/3
	2	FB5	1/3
Day-2	3	FB20	1/3
	4	FB100	1/3
Day-3	5	FB20	2/3
	5	FB5	2/3
Day-4	7	FB20	3/3
	8	FB100	2/3
Day-5	9	FB5	3/3
	10	FB100	3/3
Day-6	11	#2Diesel	2/3
	12	CB5	1/3
Day-7	13	CB20	1/3
	14	CB100	1/3
Day-8	15	CB20	2/3
	16	CB5	2/3
Day-9	17	CB20	3/3
	18	CB100	2/3
Day-10	19	CB5	3/3
	20	CB100	3/3
Day-11	21	#2Diesel	3/3

Table 5: Test Modes and Recordings

Test Fuel	Index	Test Mode	Recordings
#2 Diesel	TM1	Speed: 400 rpm Load: Residual Air boost pressure: 2.5 psi Intake air temp.: 50°C	- Power - fuel consumption - operating parameters (tempretures, pressures, flows) - Emissions - Cylinder pressure - Fuel injection pressure.
	TM2	Speed: 800 rpm Load: 984 N.m Air boost pressure: 15 psi Intake air temp.: 70°C	
	TM3	Speed: 1050 rpm Load: 1695 N.m Air boost pressure: 30.5 psi Intake air temp.: 85°C	
Biodiesel Blends	TM1	Speed: 400 rpm Fuel rate: same as #2Diesel test Air boost pressure: 2.5 psi Intake air temp.: 50°C	
	TM2	Speed: 800 rpm Fuel rate: same as #2Diesel test Air boost pressure: 15 psi Intake air temp.: 70°C	
	TM3	Speed: 1050 rpm Fuel rate: same as #2Diesel test Air boost pressure: 30.5 psi Intake air temp.: 85°C	

3.0 TEST RESULTS

3.1 Fuel Properties

Fuel gross heating value decreases with increasing percent biodiesel. It could be clearly seen that the cetane value of FB100 or CB100 was higher than that of the #2Diesel and other blends. It was also observed that the higher the percent biodiesel, the lower the fuel cloud point. The cloud points of B5 blends were similar to that of #2Diesel.

3.2 Engine Power

Observed engine power, fuel consumption and other operating parameters are shown in Tables 6 and 7. As shown in the tables, engine fuel rate, intake air temperatures, intake air pressure, coolant temperature as well as sump oil temperature were maintained closely

Table 6: Engine Operating Parameters of Frying Oil-Based Biodiesel Blends

Test Mode	Test Run No.	Engine Power (Obs.) (kW)	Fuel Rate (lb/min)	Coolant Temp. Eng. Out (°C)	Boost Air Temp. (°C)	Oil Temp. Sump (°C)	Boost Air Press. (psi)	Fuel Temp. Eng. In (°C)
#2Diesel								
TM1	#1/3	1.0	0.057	74	49	75	2.4	32
	#2/3	1.1	0.056	75	50	78	2.7	31
	#3/3	1.0	0.054	75	49	78	2.7	34
	Mean	**1.0**	**0.056**	**75**	**49**	**77**	**2.6**	**32**
TM2	#1/3	82.5	0.730	78	69	83	15.1	31
	#2/3	82.3	0.729	78	70	84	15.1	32
	#3/3	82.5	0.727	78	69	83	15.1	34
	Mean	**82.4**	**0.729**	**78**	**69**	**83**	**15.1**	**32**
TM3	#1/3	186.3	1.668	85	84	88	30.6	27
	#2/3	186.0	1.667	83	84	87	30.6	33
	#3/3	186.1	1.663	83	84	86	30.5	35
	Mean	**186.1**	**1.666**	**84**	**84**	**87**	**30.6**	**32**
FB5								
TM1	#1/3	1.1	0.056	75	48	78	2.6	30
	#2/3	1.0	0.056	74	49	78	2.5	31
	#3/3	1.0	0.056	74	49	78	2.7	32
	Mean	**1.0**	**0.056**	**74**	**49**	**78**	**2.6**	**31**
TM2	#1/3	82.1	0.730	79	70	83	15.2	31
	#2/3	82.4	0.730	77	69	83	15.1	31
	#3/3	82.3	0.734	79	70	84	15.1	30
	Mean	**82.3**	**0.731**	**78**	**70**	**83**	**15.1**	**31**
TM3	#1/3	185.2	1.669	83	84	87	30.6	31
	#2/3	186.3	1.669	81	85	86	30.6	31
	#3/3	185.9	1.664	83	84	85	30.5	30
	Mean	**185.8**	**1.667**	**82**	**84**	**86**	**30.6**	**31**
FB20								
TM1	#1/3	1.0	0.058	72	51	76	2.5	34
	#2/3	1.0	0.057	74	50	78	2.6	33
	#3/3	1.1	0.057	75	49	77	2.7	30
	Mean	**1.0**	**0.057**	**74**	**50**	**77**	**2.6**	**32**
TM2	#1/3	79.9	0.728	78	70	83	15.1	33
	#2/3	80.3	0.730	78	69	83	15.1	34
	#3/3	80.0	0.730	79	71	83	15.1	32
	Mean	**80.1**	**0.729**	**78**	**70**	**83**	**15.1**	**33**
TM3	#1/3	183.9	1.667	84	84	86	30.5	35
	#2/3	183.7	1.666	81	84	86	30.6	32
	#3/3	184.1	1.671	82	85	86	30.5	31
	Mean	**183.9**	**1.668**	**82**	**84**	**86**	**30.5**	**33**
FB100								
TM1	#1/3	0.8	0.058	71	49	78	2.5	33
	#2/3	0.8	0.062	75	50	77	2.7	33
	#3/3	0.8	0.061	75	49	76	2.5	29
	Mean	**0.8**	**0.060**	**74**	**49**	**77**	**2.6**	**32**
TM2	#1/3	71.2	0.729	80	69	83	15.1	33
	#2/3	71.2	0.729	79	70	84	15.1	32
	#3/3	71.2	0.729	78	70	83	15.1	33
	Mean	**71.2**	**0.729**	**79**	**70**	**83**	**15.1**	**33**
TM3	#1/3	169.2	1.670	84	84	86	30.6	29
	#2/3	169.2	1.667	83	84	85	30.6	31
	#3/3	169.2	1.663	82	84	86	30.6	33
	Mean	**169.2**	**1.667**	**83**	**84**	**86**	**30.6**	**31**

Table 7: Engine Operating Parameters of Canola-Based Biodiesel Blends

Test Mode	Test Run No.	Engine Power (Obs.) (kW)	Fuel Rate (lb/min)	Coolant Temp. Eng. Out (°C)	Boost Air Temp. (°C)	Oil Temp. Sump (°C)	Boost Air Press. (psi)	Fuel Temp. Eng. In (°C)
#2Diesel								
TM1	#1/3	1.0	0.057	74	49	75	2.4	32
	#2/3	1.1	0.056	75	50	78	2.7	31
	#3/3	1.0	0.054	75	49	78	2.7	34
	Mean	**1.0**	**0.056**	**75**	**49**	**77**	**2.6**	**32**
TM2	#1/3	82.5	0.73	78	69	83	15.1	31
	#2/3	82.3	0.729	78	70	84	15.1	32
	#3/3	82.5	0.727	78	69	83	15.1	34
	Mean	**82.4**	**0.729**	**78**	**69**	**83**	**15.1**	**32**
TM3	#1/3	186.3	1.668	85	84	88	30.6	27
	#2/3	186.0	1.667	83	84	87	30.6	33
	#3/3	186.1	1.663	83	84	86	30.5	35
	Mean	**186.1**	**1.666**	**84**	**84**	**87**	**30.6**	**32**
CB5								
TM1	#1/3	1.1	0.057	74	49	77	2.4	34
	#2/3	0.9	0.056	76	49	76	2.5	27
	#3/3	1.1	0.054	75	50	76	2.6	27
	Mean	**1.0**	**0.056**	**75**	**49**	**76**	**2.5**	**29**
TM2	#1/3	82.3	0.731	78	69	83	15.0	33
	#2/3	82.1	0.726	79	70	83	15.0	29
	#3/3	82.1	0.727	79	69	84	15.1	30
	Mean	**82.2**	**0.728**	**79**	**69**	**83**	**15.0**	**31**
TM3	#1/3	186.2	1.670	82	85	87	30.5	30
	#2/3	186.4	1.667	82	85	86	30.6	29
	#3/3	186.2	1.663	80	84	87	30.5	32
	Mean	**186.3**	**1.667**	**81**	**85**	**87**	**30.5**	**30**
CB20								
TM1	#1/3	1.0	0.057	74	49	76	2.6	34
	#2/3	1.0	0.056	76	50	76	2.6	29
	#3/3	1.0	0.056	75	50	76	2.8	29
	Mean	**1.0**	**0.056**	**75**	**49**	**76**	**2.7**	**31**
TM2	#1/3	80.4	0.73	78	69	83	15.1	32
	#2/3	80.4	0.729	79	70	83	15.0	31
	#3/3	80.4	0.727	79	70	83	15.0	32
	Mean	**80.4**	**0.729**	**79**	**70**	**83**	**15.1**	**32**
TM3	#1/3	185.0	1.666	83	84	87	30.6	29
	#2/3	183.9	1.668	82	85	86	30.5	34
	#3/3	184.7	1.666	81	84	85	30.5	33
	Mean	**184.5**	**1.667**	**82**	**84**	**86**	**30.6**	**32**
CB100								
TM1	#1/3	1.0	0.063	76	50	76	2.6	34
	#2/3	0.8	0.055	76	51	76	2.5	29
	#3/3	0.9	0.061	74	49	71	2.7	27
	Mean	**0.9**	**0.060**	**75**	**50**	**74**	**2.6**	**30**
TM2	#1/3	71.7	0.730	79	68	83	15.0	36
	#2/3	72.1	0.727	78	69	83	15.0	31
	#3/3	72.0	0.720	79	69	84	15.1	32
	Mean	**71.9**	**0.726**	**79**	**69**	**83**	**15.0**	**33**
TM3	#1/3	170.1	1.671	83	84	86	30.6	35
	#2/3	170.6	1.664	81	84	85	30.5	32
	#3/3	171.1	1.667	82	84	87	30.5	32
	Mean	**170.6**	**1.667**	**82**	**84**	**86**	**30.5**	**33**

for the same test mode. The FB20 reduced engine baseline power by 1.2% at TM3 and 28% at TM2. The CB20 reduced the baseline power by approximately 0.9% at TM3 and 2.4% at TM2. When the engine operated with the FB100 and the CB100 at TM3, its power was reduced by 9.0% and 8.3%, respectively. The effects of the B5 blends on engine power were not significant.

3.3 Fuel Economy

Engine brake-specific fuel consumption (BSFC) was calculated using the following equation:

$$BSFC(lb/hp \cdot h) = \frac{FuelConsumptionRate(lb/h)}{CorrectedEngineBrakeHorsepower(hp)} \qquad (1)$$

The observed engine brake power was corrected to standard conditions considering intake air temperature, fuel temperature, fuel density, heating values of fuel and altitude effects.

Engine BSFC values of the fuel blends are shown in Tables 8 and 9. The BSFC values of the FB5, CB5, FB20 and CB20 were very similar to those of the baseline fuel. Significant increases relative to baseline BSFCs were observed for the engine running with the FB100 and CB100 at the three modes. The duty-cycle weighted BSFCs are provided in Table 10. The weighted BSFCs of B5 and B20 blends were similar to that of the baseline fuel. However, the weighted BSFC of FB100 and CB100 increased baseline data by 6% and 2.5%, respectively.

Table 8: BSFC Values of Frying Oil-Based Biodiesel Blends and #2Diesel

Test Mode	Test Run No.	BSFC (lb/hp-h)				Changes (%)*		
		#2Diesel	FB5	FB20	FB100	FB5	FB20	FB100
TM1	#1/3	2.332	2.303	2.346	3.111			
	#2/3	2.394	2.379	2.417	3.148			
	#3/3	2.415	2.381	2.310	2.970			
	Mean	**2.380**	**2.354**	**2.358**	**3.076**	**-1.1**	**-0.9**	**29.2**
TM2	#1/3	0.383	0.384	0.389	0.418			
	#2/3	0.383	0.383	0.388	0.418			
	#3/3	0.380	0.386	0.391	0.418			
	Mean	**0.382**	**0.385**	**0.389**	**0.418**	**0.8**	**1.8**	**9.4**
TM3	#1/3	0.389	0.390	0.387	0.405			
	#2/3	0.387	0.387	0.388	0.403			
	#3/3	0.386	0.387	0.389	0.401			
	Mean	**0.387**	**0.388**	**0.388**	**0.403**	**0.3**	**0.3**	**4.1**

** Changes (%) = 100 x (BSFC of Biodiesel blend – BSFC of Baseline)/(BSFC of Baseline)*

Table 9: BSFC Values of Canola-Based Biodiesel Blends and #2Diesel

Test Mode	Test Run No.	BSFC (lb/hp-h)				Changes (%)*		
		#2Diesel	CB5	CB20	CB100	CB5	CB20	CB100
TM1	#1/3	2.332	2.309	2.382	2.384			
	#2/3	2.394	2.596	2.364	2.902			
	#3/3	2.415	2.220	2.377	2.752			
	Mean	**2.380**	**2.375**	**2.375**	**2.679**	**-0.2**	**-0.2**	**12.6**
TM2	#1/3	0.383	0.381	0.389	0.405			
	#2/3	0.383	0.381	0.388	0.403			
	#3/3	0.380	0.381	0.387	0.404			
	Mean	**0.382**	**0.381**	**0.388**	**0.404**	**-0.3**	**1.6**	**5.8**
TM3	#1/3	0.389	0.386	0.386	0.391			
	#2/3	0.387	0.386	0.387	0.390			
	#3/3	0.386	0.384	0.385	0.389			
	Mean	**0.387**	**0.385**	**0.386**	**0.390**	**-0.5**	**-0.3**	**0.8**

* *Changes(%) =100 x (BSFC of Biodiesel blend – BSFC of Baseline)/(BSFC of Baseline)*

3.4 Exhaust Emissions

The measured raw emissions concentrations were converted to brake-specific values. The following equation was used to calculate the composite brake-specific emissions (BSEs):

$$BSE(g/kW \cdot h) = \frac{EmissionsRate(g/h)}{ObservedEngineBrakeHorsepower(kW)} \qquad (2)$$

The gaseous emissions rate, defined as mass exhaust emissions per hour, was determined from measured emissions concentrations and the fuel consumption rate. The particulate emissions rate, defined as mass particulate emissions per hour, was calculated from particulate concentration of the diluted exhaust sample corrected for background, dilution factor and total exhaust flow rate. Detailed calculation methods can be found in section 92.132 of the EPA locomotive/locomotive engine emissions standards 40CFR Part 92 [1]. Since the ECOM AC+ is not capable of detecting total hydrocarbon (THC), the concentration of hydrocarbon was predicted using the carbon balance method. A MATLAB program was used to calculate all the specific emissions.

Raw engine exhaust emissions were converted to specific values. The AAR three-mode duty-cycle weighing factors were applied to calculate weighted CO, NOx, THC, PM emissions and BSFC. The weighing factors were 50%, 25% and 25% for TM1, TM2 and TM3, respectively. Results are given in Tables 10 and 11. The CB5 deceased baseline NOx by 1.2% with no effects to the PM emissions. Although the FB5 provided reductions in PM and CO, the NOx was increased by 8.4%. Increased NOx and reduced CO and PM emissions with FB20 and CB20 were also detected. The THC emissions changes with B5 and B20 fuels were not significant. General trending of NOx, CO, and PM changes of B5 and B20 agreed well with those from other researchers [2], except for the B100 fuels. More investigations on B100 fuels are to be conducted to investigate these observations.

Table 10: Weighted Exhaust Emissions and BSFC of Frying Oil-Based Biodiesel Blends

Emissions	Test Run No.	#2 Diesel	FB5	FB20	FB100	Changes (%) [a]		
						FB5	FB20	FB100
CO (g/kW-h)	#1/3	2.9	3.0	2.3	2.1			
	#2/3	3.0	3.2	2.6	2.1			
	#3/3	3.4	2.8	2.6	2.4			
	Mean	**3.1**	**3.0**	**2.5**	**2.2**	**-3.2**	**-19.4**	**-29.0**
NOx (g/kW-h)	#1/3	17.2	19.2	17.3	28.1			
	#2/3	16.7	18.4	18.9	28.1			
	#3/3	16.3	16.7	17.8	29.0			
	Mean	**16.7**	**18.1**	**18.0**	**28.3**	**8.4**	**7.8**	**69.5**
THC[b] (g/kW-h)	#1/3	0.19	0.20	0.19	0.23			
	#2/3	0.20	0.20	0.20	0.24			
	#3/3	0.20	0.19	0.20	0.25			
	Mean	**0.20**	**0.20**	**0.20**	**0.24**	**0.0**	**0.0**	**20.0**
PM (g/kW-h)	#1/3	0.15	0.16	0.13	0.27			
	#2/3	0.16	0.14	0.14	0.23			
	#3/3	0.17	0.13	0.13	0.25			
	Mean	**0.16**	**0.14**	**0.13**	**0.25**	**-12.5**	**-18.8**	**56.3**
BSFC (lb/hp-h)	#1/3	0.402	0.403	0.403	0.426			
	#2/3	0.401	0.401	0.404	0.426			
	#3/3	0.399	0.402	0.405	0.424			
	Mean	**0.401**	**0.402**	**0.404**	**0.425**	**0.3**	**0.7**	**6.0**

(a)Changes(%) =100 x (Emission of Biodiesel blend – Emissions of Baseline)/(Emissions of Baseline).
(b)Values were calculated based on exhaust carbon balance method.

Table 11: Weighted Exhaust Emissions and BSFC of Canola-Based Biodiesel Blends

Emissions	Test Run No.	#2 Diesel	CB5	CB20	CB100	Changes (%) [a]		
						CB5	CB20	CB100
CO (g/kW-h)	#1/3	2.9	3.0	2.8	2.2			
	#2/3	3.0	2.8	2.6	2.0			
	#3/3	3.4	2.8	2.6	2.3			
	Mean	**3.1**	**2.9**	**2.7**	**2.2**	**-6.5**	**-12.9**	**-29.0**
NOx (g/kW-h)	#1/3	17.2	16.5	18.2	25.3			
	#2/3	16.7	16.5	17.8	25.1			
	#3/3	16.3	16.4	17.7	25.8			
	Mean	**16.7**	**16.5**	**17.9**	**25.4**	**-1.2**	**7.2**	**52.0**
THC[b] (g/kW-h)	#1/3	0.19	0.19	0.20	0.23			
	#2/3	0.20	0.19	0.20	0.22			
	#3/3	0.20	0.19	0.20	0.23			
	Mean	**0.20**	**0.19**	**0.20**	**0.23**	**-5.0**	**0.0**	**15.0**
PM (g/kW-h)	#1/3	0.15	0.15	0.13	0.27			
	#2/3	0.16	0.16	0.15	0.28			
	#3/3	0.17	0.16	0.15	0.24			
	Mean	**0.16**	**0.16**	**0.14**	**0.26**	**0.0**	**-12.5**	**62.5**
BSFC (lb/hp-h)	#1/3	0.402	0.400	0.402	0.413			
	#2/3	0.401	0.399	0.403	0.410			
	#3/3	0.399	0.397	0.401	0.411			
	Mean	**0.401**	**0.399**	**0.402**	**0.411**	**-0.5**	**0.3**	**2.5**

(a)Changes(%) =100 x (Emissions of Biodiesel blend – Emissions of Baseline)/(Emissions of Baseline).
(b)Values were calculated based on exhaust carbon balance method.

Smoke opacity results are given in Tables 12 and 13. The smoke opacity decreased with increasing percent biodiesel. The smoke of frying oil biodiesel showed more significant improvements compared with that of the canola-based biodiesel.

Table 12: Smoke Opacity of Frying Oil-Based Biodiesel Blends and #2Diesel

Test Mode	Test Run No.	Smoke Opacity				Changes (%)*		
		#2Diesel	FB5	FB20	FB100	FB5	FB20	FB100
TM1	#1/3	0.3	0.3	0.3	0.4			
	#2/3	0.4	0.2	0.3	0.3			
	#3/3	0.5	0.4	0.2	0.3			
	Mean	**0.4**	**0.3**	**0.3**	**0.3**	**-25.0**	**-25.0**	**-25.0**
TM2	#1/3	0.5	0.5	0.4	0.4			
	#2/3	0.7	0.5	0.4	0.4			
	#3/3	1.1	0.7	0.4	0.4			
	Mean	**0.8**	**0.6**	**0.4**	**0.4**	**-25.0**	**-50.0**	**-50.0**
TM3	#1/3	1.5	1.4	0.9	0.5			
	#2/3	1.6	1.1	0.9	0.6			
	#3/3	1.6	1.5	0.7	0.4			
	Mean	**1.6**	**1.3**	**0.8**	**0.5**	**-18.8**	**-50.0**	**-68.8**

** Changes(%) = 100 x (Emissions of Biodiesel blend – Emissions of Baseline)/(Emissions of Baseline).*

Table 13: Smoke Opacity of Canola-Based Biodiesel Blends and #2Diesel

Test Mode	Test Run No.	Smoke Opacity				Changes (%)*		
		#2Diesel	CB5	CB20	CB100	CB5	CB20	CB100
TM1	#1/3	0.3	0.5	0.3	0.5			
	#2/3	0.4	0.5	0.4	0.5			
	#3/3	0.5	\	\	\			
	Mean	**0.4**	**0.5**	**0.4**	**0.5**	**25.0**	**0.0**	**25.0**
TM2	#1/3	0.5	0.6	0.7	0.7			
	#2/3	0.7	0.5	0.5	0.5			
	#3/3	1.1	\	\	\			
	Mean	**0.8**	**0.6**	**0.6**	**0.6**	**-25.0**	**-25.0**	**-25.0**
TM3	#1/3	1.5	1.4	1.3	1			
	#2/3	1.6	1.2	1.1	1.3			
	#3/3	1.6	\	\	\			
	Mean	**1.6**	**1.3**	**1.2**	**1.2**	**-18.8**	**-25.0**	**-25.0**

** Changes(%) = 100 x (Emissions of Biodiesel blend – Emissions of Baseline)/(Emissions of Baseline).*

3.5 Heat Release Rate (HRR)

Cylinder pressures were collected during the runs. They were used to calculate apparent net heat release rate based on the first law of thermodynamics to the content of the combustion chamber [3]. The heat release rate of a test mode was plotted in terms of heat-release-rate versus crank-angle. Plots of the three modes are shown in Figures 3 to 8.

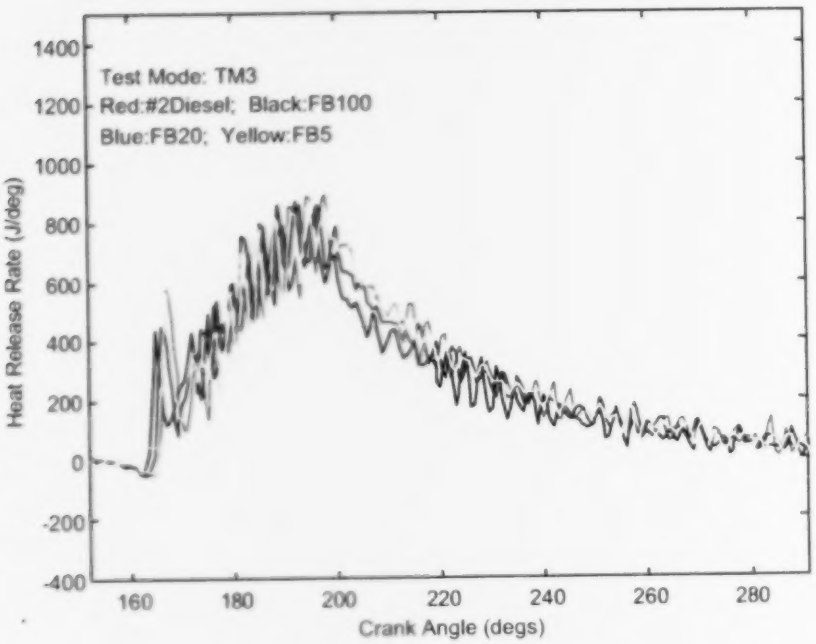

Figure 3: HRR of Frying Oil-Based Biodiesel Blends and #2Diesel at TM3

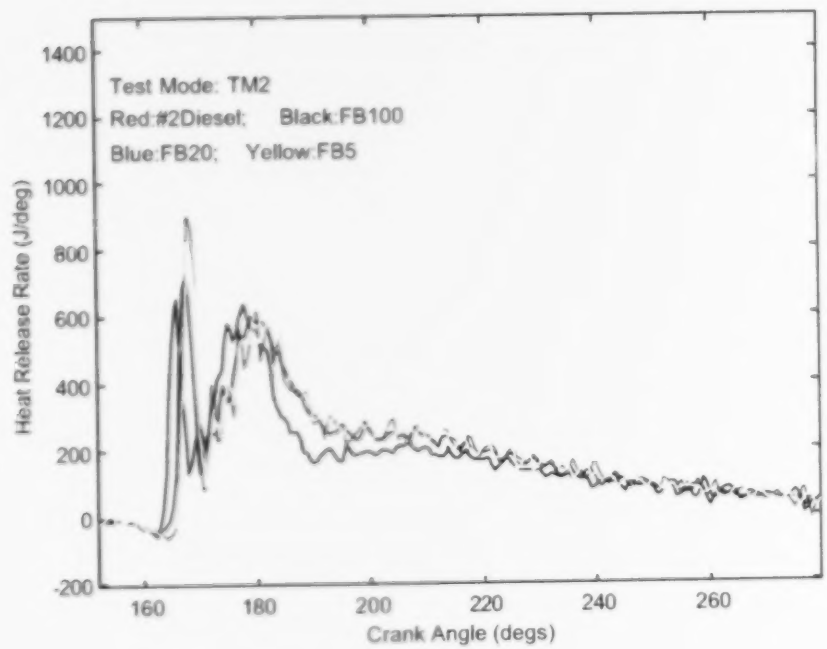

Figure 4: HRR of Frying Oil-Based Biodiesel Blends and #2Diesel at TM2

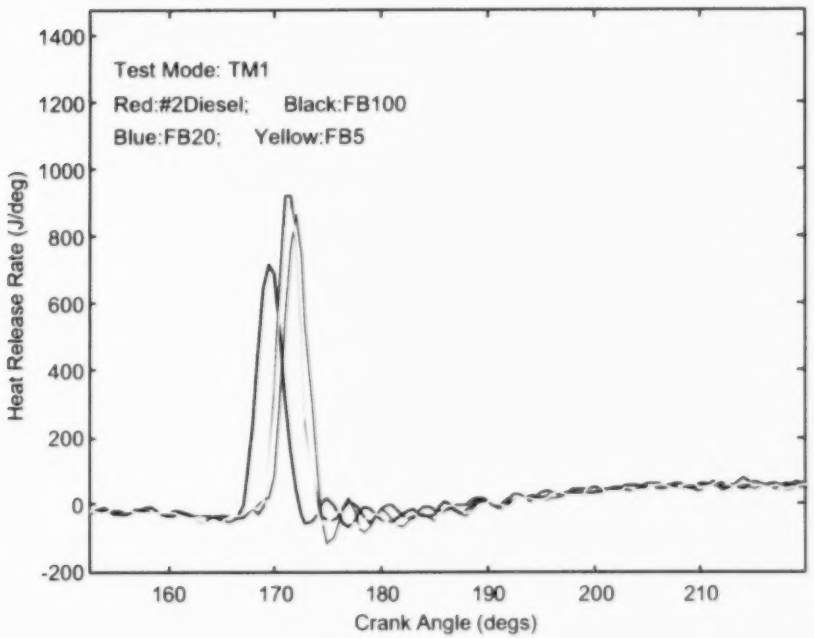

Figure 5: HRR of Frying Oil-Based Biodiesel Blends and #2Diesel at TM1

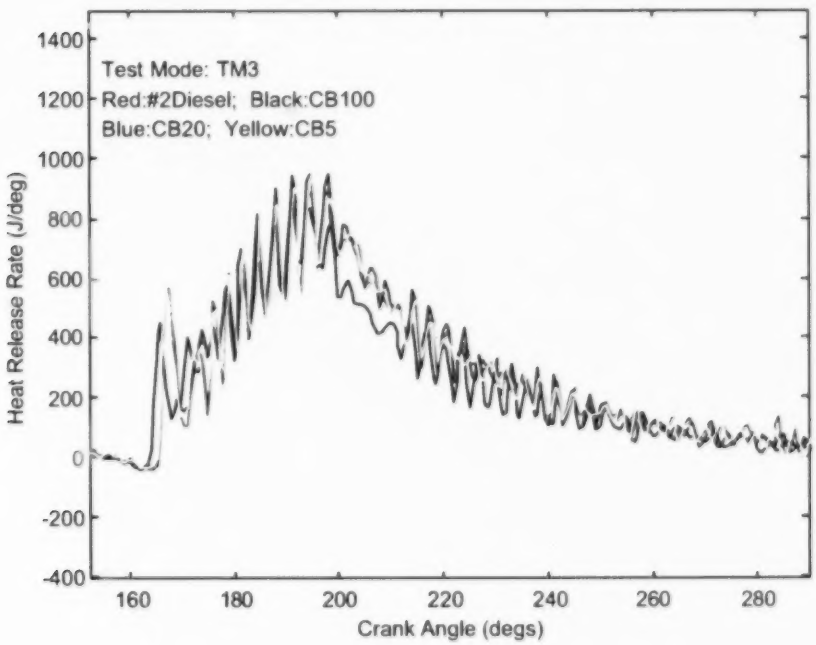

Figure 6: HRR of Canola-Based Biodiesel Blends and #2Diesel at TM3

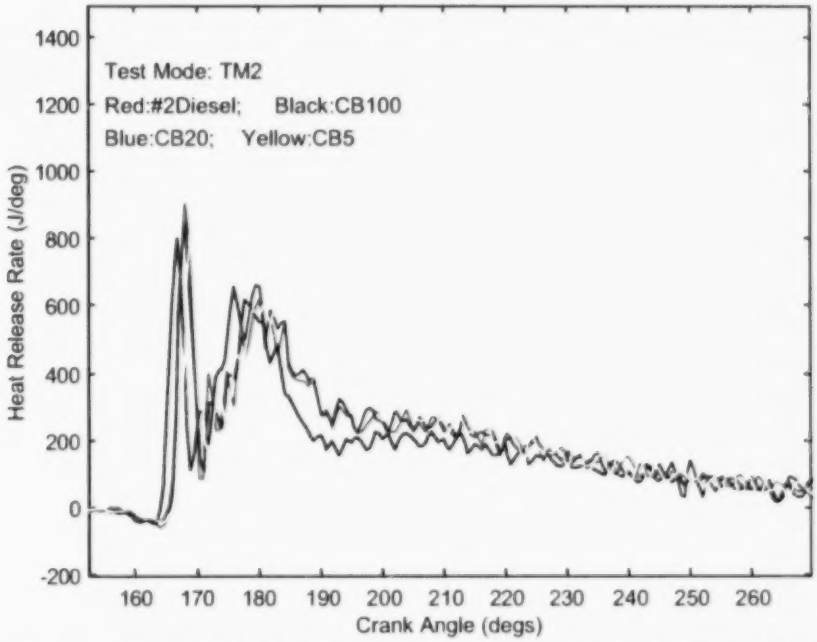

Figure 7: HRR of Canola-Based Biodiesel Blends and #2Diesel at TM2

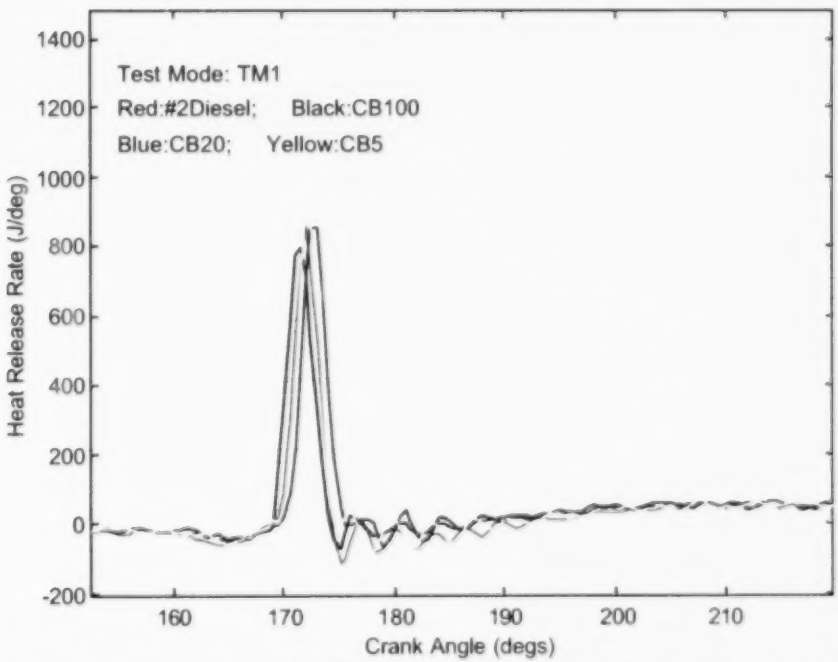

Figure 8: HRR of Canola-Based Biodiesel Blends and #2Diesel at TM1

The HRR profiles at different modes show that the B20 and B100 fuels have shorter ignition delays compared with that of the #2Diesel. The ignition delays of B5 fuels are very similar to that of the baseline fuel. The longer delays allow more fuel/air mix ready to burn during the premixing period, so the peak premixing HRR increases. Significant reduction of the mixing-controlled phase HRR of the B100 fuels can be observed at a period shortly after the peak position. Injection pressure patterns of B20 and B5 blends were found basically the same as that of the #2Diesel (see section 3.6). The reduced observed engine powers with B20 blends are attributed to the shorter combustion delay and lower fuel heating value.

3.6 Fuel Injection Pressure (FIP)

Fuel injection pressures are shown in Figures 9 to 14. Similar injection pressure patterns of B5 and B20 blends as compared with #2Diesel were observed. Due to high fuel viscosity, the FB100 increased baseline peak injection pressure by approximately 18%, and CB100 increased the baseline by about 15% at TM3. For the same fuel rate, the CB100 and FB100 had shorter injection durations due to the higher fuel densities (see Table 3).

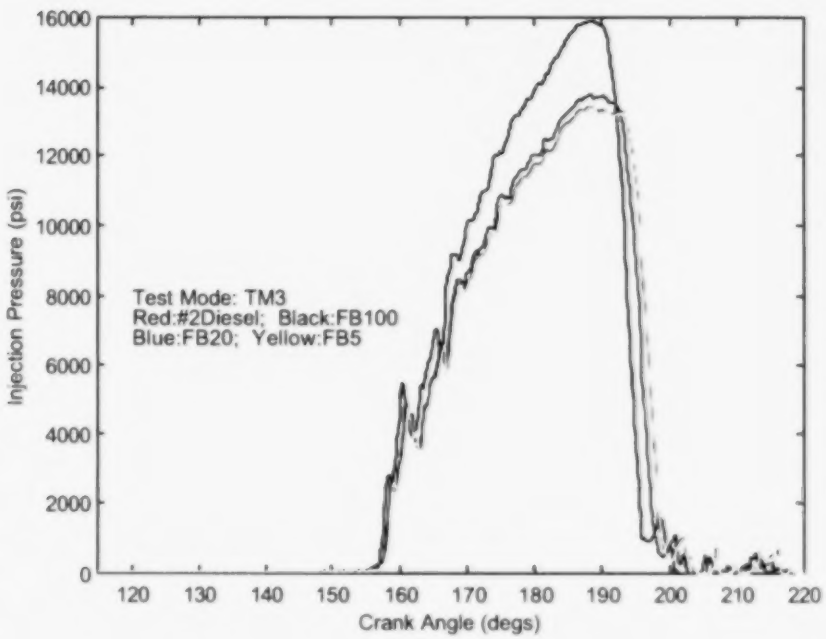

Figure 9: FIP of Frying Oil-Based Biodiesel Blends and #2Diesel at TM3

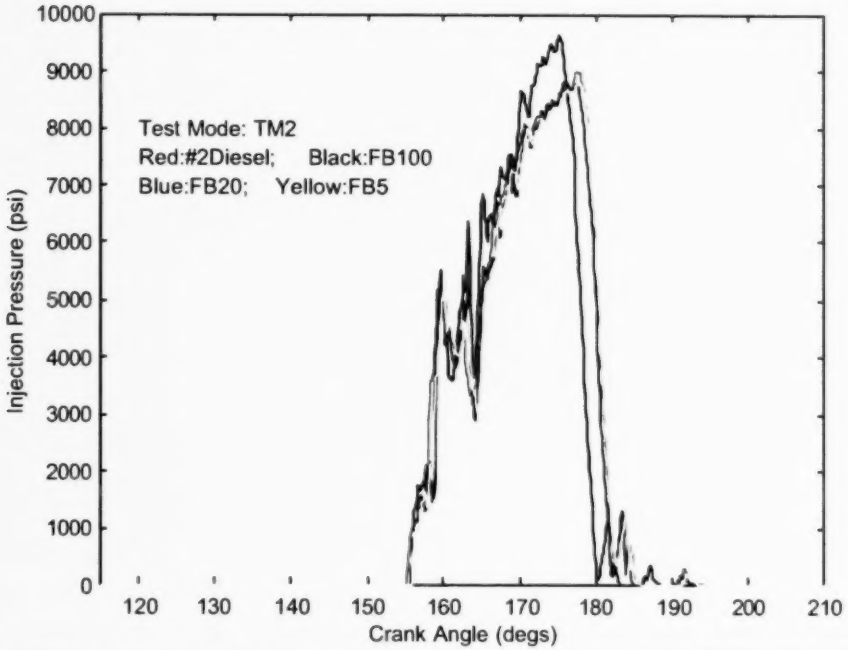

Figure 10: FIP of Frying Oil-Based Biodiesel Blends and #2Diesel at TM2

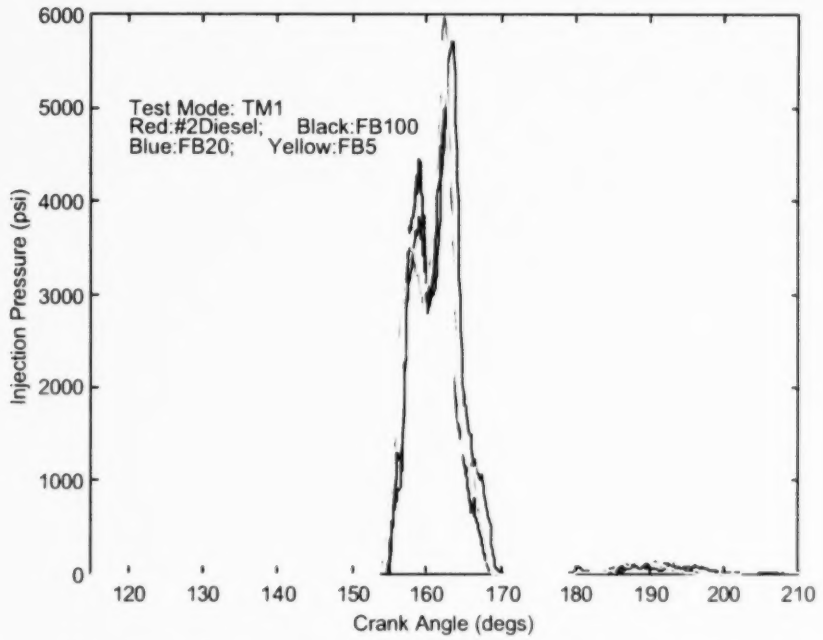

Figure 11: FIP of Frying Oil-Based Biodiesel Blends and #2Diesel at TM1

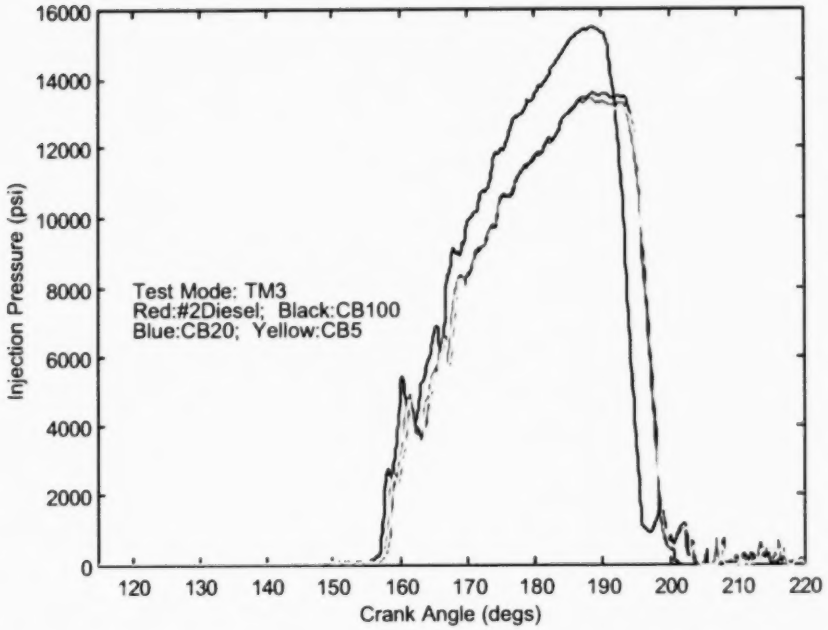

Figure 12: FIP of Canola-Based Biodiesel Blends and #2Diesel at TM3

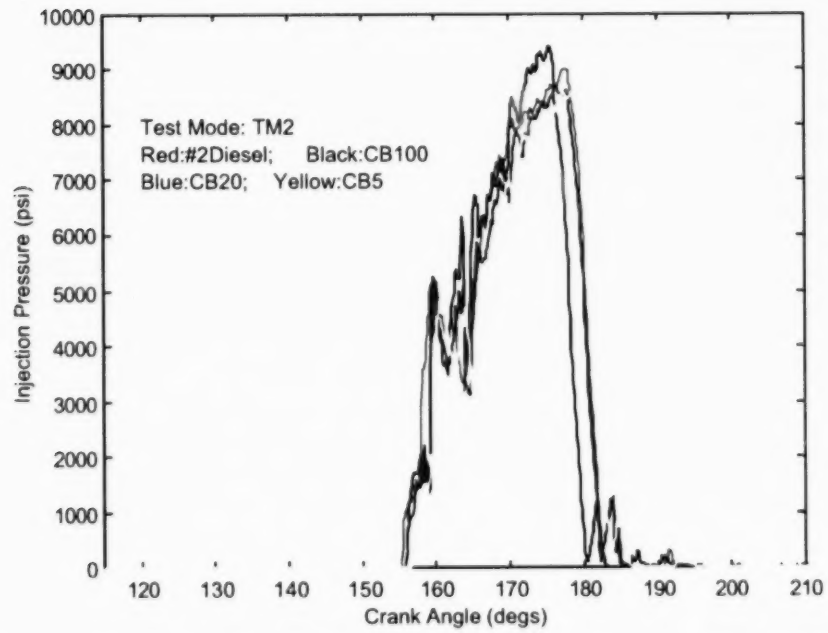

Figure 13: FIP of Canola-Based Biodiesel Blends and #2Diesel at TM2

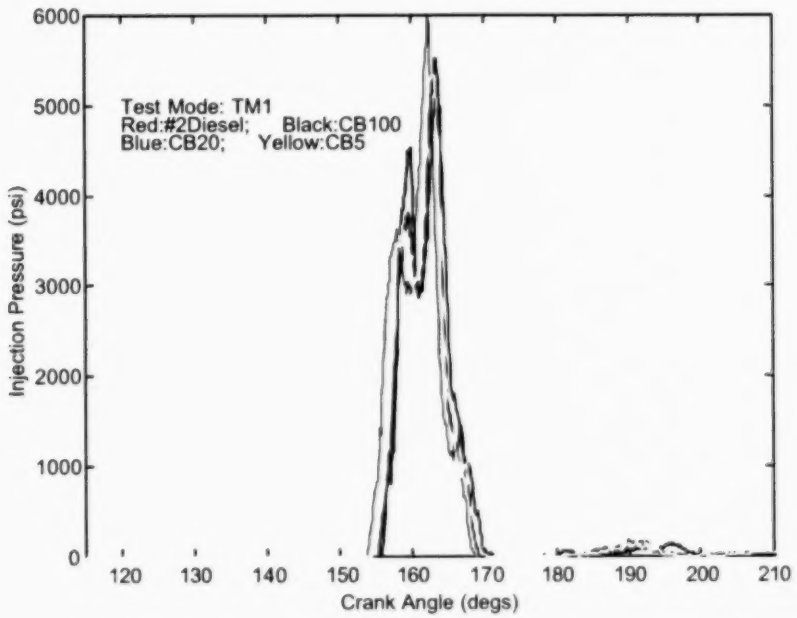

Figure 14: FIP of Canola-Based Biodiesel Blends and #2Diesel at TM1

4.0 CONCLUSIONS

When the engine fuel rate was maintained constant, the injection pressure patterns of the CB5 and the FB5 were comparable to that of the #2Diesel. However, due to nature of the biodiesel fuels, a shorter ignition delay was observed and this led to a lower premixed heat release rate as compared with #2Diesel. The B5 fuels could maintain engine baseline power and fuel economy with the additional benefits of reduced CO, PM, and smoke emissions. The FB5 increased engine NOx emissions by about 8%. A slight reduction in NOx emissions with CB5 was observed.

The CB20 and FB20 showed a slight reduction in engine power. This could be due the ignition delay and lower heating valuve, since the injection pressure trends of the fuels are similar to that of the #2Diesel. Although the two fuels could significantly reduce engine CP, PM and smoke emissions, they increased engine NOx emissions.

Generally the observations on B5 and B20 fuels agreed well with other investigators work. However, other people's results for B100 fuels, such as reduced PM, could not be repeated in this work. The heat release rate and injection pressure curves showed that when the engine fuel rate is maintained constant, improper injection pressure of the B100 fuels may lead to increased unburned hydrocarbon in the after-combustion period and, eventually, the increased PM and THC emissions. Therefore, more work, such as fine tuning the fuel injection pressure and performing a durability analysis of fuel system

components with increased injection pressure, is necessary in order to really apply the B100 fuels.

In consideration of other factors such as winter fuel storage, cost issues and Canadian biodiesel supply capacity, the use of CB5, FB5 and FB20 will be more practical at the current stage for the Canadian railway locomotive fleet.

5.0 RECOMMENDATIONS

The following work is recommended in two phases:

Phase 1: Based on the results of this project, three candidate biodiesel blends should be selected to conduct laboratory tests on a GE and an EMD locomotive. Since soybean biodiesel could not be tested in the single-cylinder engine, it could be combined with the selected candidate blends and tested in this phase. One or two biodiesel blends could be selected for further tests.

Phase 2: A proper commuter railway should be selected to conduct field tests on a number of in-service locomotives with biodiesel fuels selected in the first phase.

REFERENCES

1. "Emission Standards for Locomotives and Locomotive Engines-Part II", 40 Code of Federal Register, Part 92, Environmental Protection Agency, U.S.A.

2. "A Comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions", EPA420-P-02-001, Environmental Protection Agency, U.S.A.

3. J. B. Heywood, "Internal Combustion Engine Fundamentals", McGraw-Hill, 1988.